Adapting Brillouin spectrum for slow light delays

Th. Schneider, R. Henker, K.-U. Lauterbach and M. Junker

Described is a simple method to adapt Brillouin spectrum properties such as slope, bandwidth and gain for stimulated Brillouin scattering based slow light systems and other applications. As an example, enhancement of time delay at constant gain and pump power owing to an increased Brillouin slope, is presented.

Introduction: Controlling the velocity of light pulses by light has attracted much recent interest since it offers the possibility to develop practical devices for telecommunications systems such as optical delay lines, optical buffers and optical equalisers. Beside other methods the exploitation of the group velocity alteration in optical fibres due to the nonlinear effect of Brillouin scattering (BS) is of special interest [1]. This is for several reasons: (i) Optical fibres can be integrated seamlessly into existing systems and off-the-shelf telecom equipment can be used. (ii) SBS works in all types of fibres and in the fibres entire transparency range. (iii) It requires only small pump powers for a relatively large pulse delay. With SBS in optical fibres the group velocity can be controlled between 71000 km/s and more than the speed of light in a vacuum [2].

Most experiments presented so far use the natural Brillouin gain of the fibre which will be produced around a frequency $f_P - f_B$ by a counter-propagating pump wave with an optical frequency f_P. The frequency shift f_B between the pump and the line centre of the Brillouin gain is around 11 GHz and the linewidth Δf_B is around 30 MHz in standard singlemode fibres (SSMFs) at a wavelength of 1550 nm. To adapt the bandwidth the Brillouin gain can be broadened by a modulation [2, 3]. A counter-propagating wave with a frequency in the gain bandwidth will be amplified (Stokes amplification) and delayed. At a frequency around $f_P + f_B$ the SBS process generates a loss in the fibre (anti-Stokes absorption).

The maximum pulse delay in SBS delay lines is restricted by the pump depletion due to the inherent amplification process. In recent experiments the pulse delay was decoupled from the amplification [4, 5] which leads to very high pulse delays of around 100 ns [6] in just one fibre loop. This can be done by a superposition of a Brillouin gain with a loss. This method shifts the baseline of the Brillouin gain and decreases the gain maximum. On the other hand, it requires very high pump powers since the slope of the Brillouin spectrum is not altered by this method. Here we show a simple method to adapt all properties of the Brillouin spectrum, such as bandwidth, slope and gain, to the given application. As an example we investigated the enhancement of the time delay due to an increased slope at constant gain and pump power. In the presented method delay and Brillouin gain are decoupled as well. At the same time the slope of the Brillouin gain is altered, which increases the delay for a constant power, gain and Brillouin bandwidth.

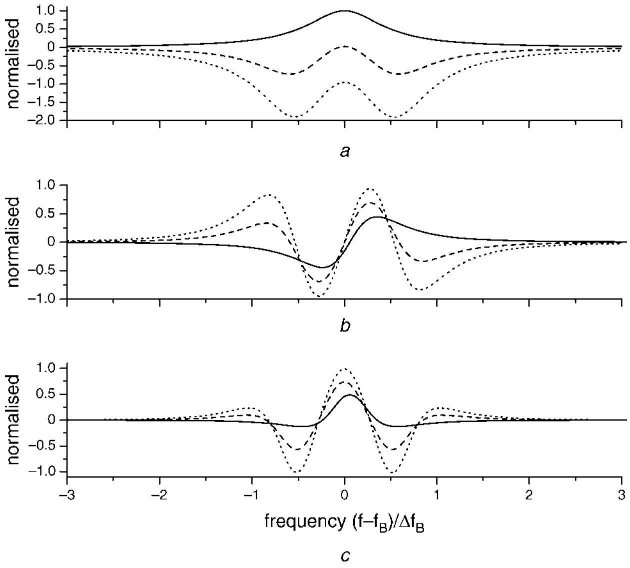

Fig. 1 *Simulated Brillouin gain, phase, and group index change*

a Gain
b Phase
c Group index change Δn_g

If at the wing of a Stokes gain an anti-Stokes loss is introduced the slow light delay arising from the wing of the anti-Stokes resonance increases the delay at the centre of the Stokes resonance which was used to enhance the slow light bandwidth [7]. If two anti-Stokes resonances are introduced at the left and right wing of the Stokes resonance they can further enhance the time delay in the centre. Fig. 1 shows the gains, the accompanied phase shifts and the related change of the group index for three different shapes of the Brillouin gain. The natural Lorentzian slope which is produced by one pump laser is shown by the solid line. If two anti-Stokes resonances, with the same power as the Stokes resonance, are introduced at the wings the slope of the phase changes. Therefore, the group index change will be increased as can be seen from the dashed line in Fig. 1. The slope of the phase alteration and the group index alteration can be further enhanced if the powers of the anti-Stokes resonances are increased as can be seen from the dotted line in Fig. 1. At the same time, due to the added loss, the overall gain and therefore the amplification by Brillouin scattering will be reduced. This circumvents the pump depletion for high delay times. By adding the loss spectra the bandwidth of the Brillouin gain, and hence the slow light bandwidth, is reduced only slightly.

Hence, the introduction of the anti-Stokes resonances, which can be produced by an additional pump laser with a frequency separation which corresponds to two times the Brillouin shift ($f_{P2} = f_P - 2f_B$), increases not only the time delay but it increases with pump power as well. At the same time the Brillouin gain will be reduced by this method which circumvents pump depletion. Therefore, with this method a drastic enhancement of the pulse delay might be possible.

With the presented method all properties of the Brillouin spectrum in the fibre can be tailored. This opens the possibility to adapt the bandwidth, the amplification and the delay to the given slow light application. But the method can also be used for other applications such as optical filtering or separate amplification. A broad and flat Brillouin gain, produced by an external modulation of the pump laser with a pulse pattern [8], can be superimposed with two narrow anti-Stokes loss spectra in order to produce sharp edges for instance. This slope would lead to a broad slow light bandwidth by an extended delay [9] and, by changing the absolute gain, to a bandpass filter or amplifier. Another possibility is the superposition of a loss in the middle with two gains at its edges. This configuration would lead to a pulse acceleration for fast light applications and to a kind of notch filter.

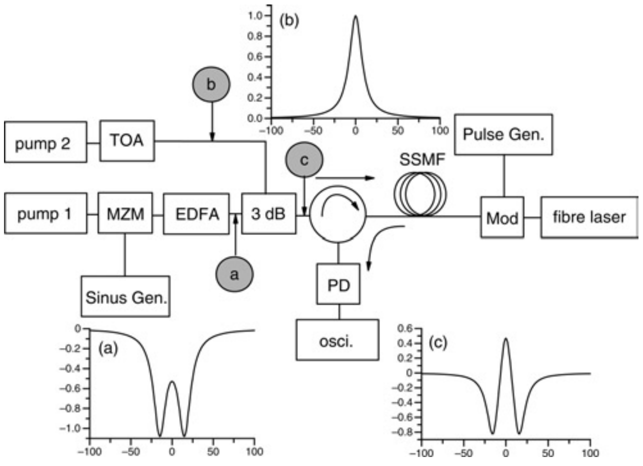

Fig. 2 *Experimental setup*

Experimental setup: To test our idea we generated a Stokes gain together with two anti-Stokes loss resonances similar to Fig. 1 with the experimental setup shown in Fig. 2. The Brillouin gain was generated by a distributed feedback (DFB) laser diode (pump 2) at a wavelength of around 1550 nm. The spectrum of the Brillouin gain can be seen in inset (b). Pump 1 is another DFB laser diode which generates the anti-Stokes loss resonances. To do this it is shifted in frequency around 22 GHz in respect to pump 2 by temperature control. Since we need two anti-Stokes resonances the wave from pump 1 is amplitude modulated with a Mach-Zehnder modulator (MZM). For the modulation we drove the MZM with a sinusoidal signal of 30 MHz in a suppressed carrier regime. Hence, only the two first order sidebands, separated by 30 MHz, can be seen in the output of the modulator; each produces an anti-Stokes loss in the fibre as can be seen from inset (a).

The gain can be controlled by a tunable optical attenuator (TOA) whereas the loss can be adjusted by an erbium-doped fibre amplifier (EDFA). Gain and loss waves are superimposed in a 3 dB coupler to produce the required spectrum, as can be seen from inset (c). The pump waves are coupled into a 50 km SSMF via a circulator. We used such a very long fibre in order to minimise the required pump powers. From the other side the very narrow wave (< 1 MHz) of a fibre laser was coupled into the same fibre via a modulator. The modulator (Mod) was driven by a waveform generator (Gen) in order to produce pulses with a temporal duration of around 35 ns. The delayed pulse was detected by a photodiode (PD) and interpreted by an oscilloscope (osci).

Results: The measured Brillouin gain and loss spectrum in the fibre is shown in the inset of Fig. 3. As can be seen, the setup produces the required behaviour. The pulse delay against power of the gain laser for four different powers of the loss spectrum can be seen in Fig. 3. The introduction of the loss spectrum leads to a higher increase of pulse delay with pump power. This means the group index was enhanced by this method. Without loss we have only the Brillouin gain, which delays the pulse. For a pump power of 6.3 dBm this leads to a pulse delay of around 16 ns. If the two loss spectra are introduced, with a rather low power of 2.65 dBm, for the same pump power the delay is increased to 20 ns. If the two loss spectra are generated with a high power of 8.13 dBm the delay reaches a value of around 31 ns, which is nearly twice that as without loss.

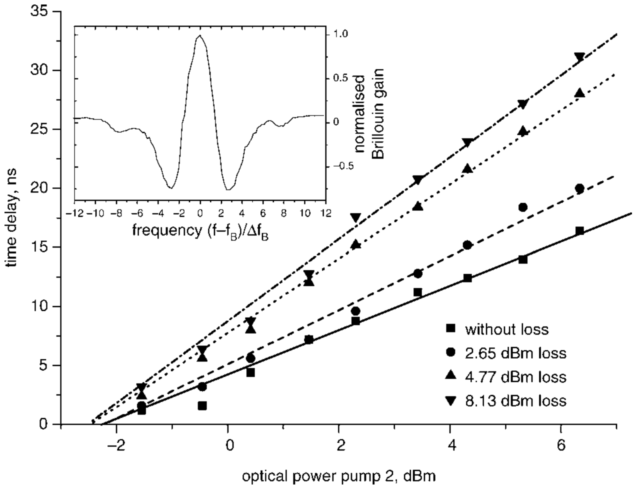

Fig. 3 *Pulse delay against optical power of pump laser 2 for different powers of loss, generated by laser 1*

Inset: Example for measured spectrum of Brillouin gain in the fibre

Conclusion: We have shown a simple method for the tailoring of Brillouin spectrum properties such as slope, bandwidth and gain. As an example we investigated our technique for slow light delay enhancement. With this method for a constant gain and a nearly constant Brillouin bandwidth we achieved approximately a doubling of the pulse delay.

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